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CLIMATE CHANGE IMPLICATIONS FOR THE BALLONA WETLANDS RESTORATION

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Abstract

Low-lying coastal wetlands are particularly vulnerable to sea level change and other potential impacts of climate change. Parties responsible for restoration and long-term management of these coastal wetlands need to understand the potential extent of these impacts and plan adaptation strategies accordingly. Using the Ballona Wetlands as a case study, this research explored a new approach to integrating climatic and hydrological models for studying the impacts of sea level rise and extreme rainfall patterns, the two changes most likely to result from climate change. Under this study, multiple models were applied to simulate the impacts of various sea level and precipitation scenarios to two wetland restoration alternatives under development. In total, a suite of 36 model simulations are performed to investigate the inundation impacts of either single sea level rise (SLR) or precipitation event, or combination of various scenarios.

The results of the study demonstrate that in the event of SLR, habitats restored according to either alternative will experience various levels of impacts. However, a restoration alternative that can accommodate the transgression of habitats upslope may provide more sustainability and support more diverse marsh habitats in the long term. The study results also validate one of the widely held assumptions that tidal wetlands in Southern California, including the Ballona Wetlands Ecological Reserve (BWER), are inherently highly vulnerable to SLR because they typically exist within a very narrow elevation range set primarily by the tidal frame (high and low tides), which is approximately 2 m in the region. The results of this investigation may help in planning coastal wetlands restoration projects in the future. Finally, the study demonstrates that the integrated modeling approach is feasible and can be applied to assessing the impacts of climate change on other coastal wetlands habitats.

Introduction

There is growing and increasingly firm evidence that more emission of anthropogenic greenhouse gas is causing the global average surface air and ocean temperatures to increase. As the climate warms, sea level rises due to melting of land-based ice and thermal expansion of oceans and seas. Global temperature rise may also result in many other potential impacts including, but are not limited to higher storm surge and more occurrence of extreme precipitation events—both flood and drought.

Low-lying coastal regions such as wetlands are particularly vulnerable to the impacts of climate change, especially to sea level rise and changing precipitation characteristics. Tidal wetlands exist within a narrow range of elevations, set primarily by tidal frame (Zedler and Cox 1985; Silvestri et al., 2005). A small change in the tidal frame due to sea level rise would result in the movement of the vertical distribution of tidal habitats, depending on the physical condition gradients (Kirwan et al., 2010). Furthermore, it may be very difficult for coastal wetlands in Southern California to adapt to sea level rise through transgression of habitats to higher elevation under existing conditions due to urbanization of the surrounding land and hydrological modifications to the system. For these reasons, it is very important for restoration planners and resource managers to understand the extent of these impacts and develop and implement adaptation strategies accordingly. Ideally, the adaptation measures can be built in early on during the restoration planning stage.

The Ballona Wetlands provide a good location for a case study on the potential impacts of climate change. The Ballona Wetlands are one of the last remaining major coastal wetlands in Southern California. The upstream watershed is one of the most developed regions in the United States, with urbanized areas accounting for approximately 80% of the 130-square-mile watershed (Fig. 1).

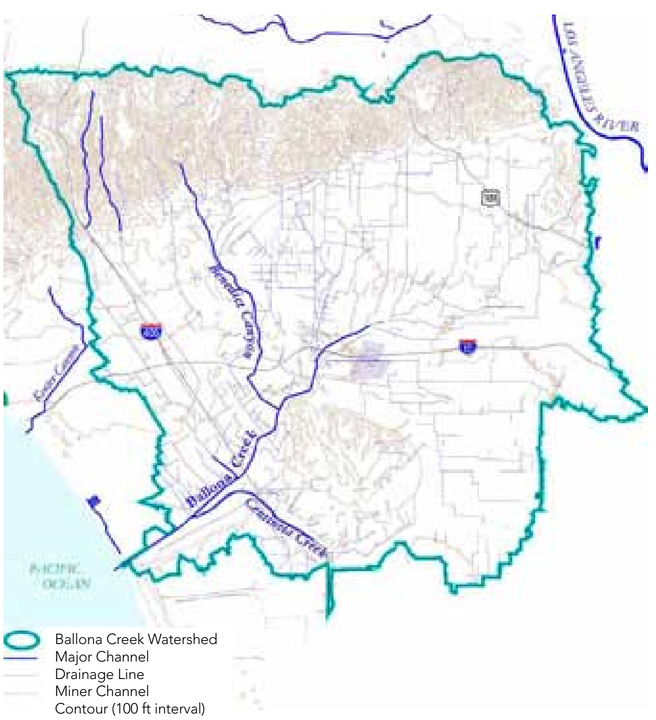

FIG. 1. Map of the Ballona Creek Watershed. Figure courtesy of PWA (2006).

Development in and around the historical Ballona Wetlands has caused changes in hydrology and altered the size and function of the native habitats in several ways, including change in land surface elevation and permeability as a result of the deposits of fill from the construction of Marina Del Rey, construction of highways and railroads, change in tidal exchange patterns due to construction of levees and culverts, and conversion of marsh to agricultural fields.

In 2004, the State of California took title to approximately 600 acres of the remaining Ballona Wetlands (Fig. 2) and created the Ballona Wetlands Ecological Reserve (BWER). The state is working with stakeholders to plan the restoration of the BWER, with the goal of "restoring, enhancing, and creating estuarine habitat and processes in the Ballona ecosystem to support a natural range of habitats and functions, especially as related to estuarine dependent plants and animals," among other things (PWA 2006). In order to achieve this goal, the Ballona Wetlands Restoration Project initiated by the state stressed in its plan the importance of "restoring inherent ecological processes, improving sustainability and resiliency to adapt to climate change and other environmental changes" (BWRP 2012). A better understanding of the potential impacts of climate change on the Ballona Creek Watershed and Wetlands will help to accomplish this objective.

Analysis of climate change impacts at the concept design and feasibility analysis stage of restoration, as in the case of BWER, is more advantageous, as restoration alternatives can be refined to be more adaptive to the impacts of climate change before proceeding to formal review. The purpose of this study is to analyze the potential climate change impacts to habitats in the BWER under different restoration alternatives. The study was conducted by applying various climate change scenarios, primarily sea level rise and changes in precipitation, to the hydrologic conditions in the watershed and hydraulic conditions of the wetlands. Model simulations were conducted to predict changes in tidal heights and area of inundation under two restoration alternatives. The potential changes in the type and acreage of habitats within the BWER due to changes in the period, depth and frequency of tidal inundation were also investigated.

Methodology

Modeled Sea Level Rise and Precipitation Change Scenarios

While there are many potential impacts of climate change globally, this study focuses on the implications of potential changes in sea level and precipitation. These are two of the major impacts of climate change to which low-lying coastal regions such as wetlands are particularly vulnerable. For the impacts of sea level rise, several projections were researched and compared, including the IPCC (2007) projections and more recent studies by Kerr (2009) and Vermeer and Rahmstorf (2009). The state of California is currently using projections from 101 to 140 cm by 2100 (CO-CAT, 2010), based on Vermeer and Rahmstorf (2009); this takes into account the rapid changes resulting from ice sheet breaks and is considered

FIG. 2. Existing Ballona Wetlands Area. Figure courtesy of PWA (2008).

more realistic. For these reasons, scenarios applying California's projections (100 and 140 cm) are applied in this study.

Unlike sea level, changes in precipitation are more evident in frequency and magnitude of extreme precipitation events than the changes in mean precipitation. Changes also result from climate patterns such as El Nino–Southern Oscillation (ENSO) and northern and southern hemisphere annual modes. There have been a number of studies of these changes since 1970 in the western United States and Southern California (e.g., Karl and Knight 1998; Madsen and Figdor 2007; Pryor et al. 2009; Mass et al. 2010; Higgins et al. 2007; Karl et al. 2009). According to these studies, even if there is no change in mean precipitation, the frequency of heavy precipitation events and incidence of drought have both increased, and will continue to increase in many areas, including Southern California (IPCC 2007). On the other hand, modeling studies of extreme precipitation changes under future conditions in Southern California demonstrate conflicting results (e.g., Bell et al. 2004; Diffenbaugh et al. 2005; Kim 2005), and all modelers have emphasized the high level of uncertainty in their projections for the Southern California region. Given these uncertainties, a suite of hypothetic precipitation scenarios ranging from a 25% decrease to a 25% increase in extreme precipitation are used in this study.

Modeled Wetland Restoration Plan Alternatives

The study applies and integrates multiple models under various climate change scenarios to two potential wetland restoration plans for the BWER. Through the restoration planning process, planners considered various design alternatives for the BWER, ranging from minor changes to the existing conditions to major earth moving and creation of a sinuous creek channel and unrestricted tidal flows to the wetland. For this study, we modeled impacts to a design known as Alternative 5, and a revised version of Alternative 5, known as the Revised Alternative. Alternative 5 (Alt5) involves removing the Ballona Creek flood control levees and excavating fill alongside the creek to allow it to meander through its floodplain and restore a large contiguous salt marsh plain (Fig. 3a). Revised Alternative 5 (or RevAlt5) accommodates some existing infrastructure constraints at the site, and includes a continuous slope from subtidal through upland habitats to allow the migration of habitats in the event of sea level rise. In RevAlt5, the channel meanders less than in Alt5, and the existing flood control levees remain in place in the far eastern (upstream) portion of the site (Fig. 3b). Note that these alternatives examined by this study are the original Alt5 from 2008 and RevAlt5 from 2009. They are not the alternatives from the Environmental Impact Reporting process; those have not been finalized, and these are only two of the graphic options that have been in development.

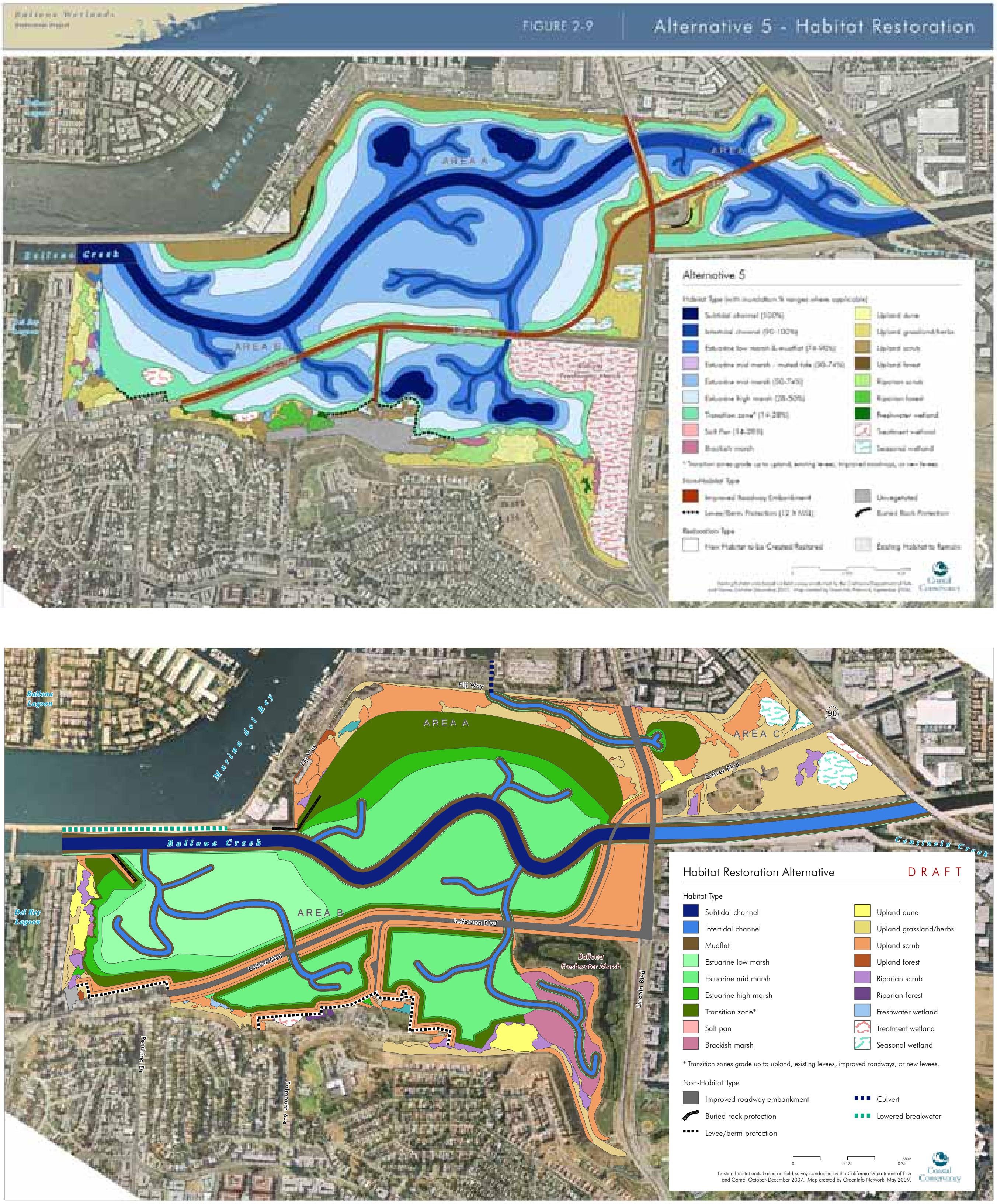

FIG. 3. Maps of wetlands for the 2008 restoration Alternative 5 (Alt5) (a) and the revised restoration Alternative 5 (RevAlt5) (b).

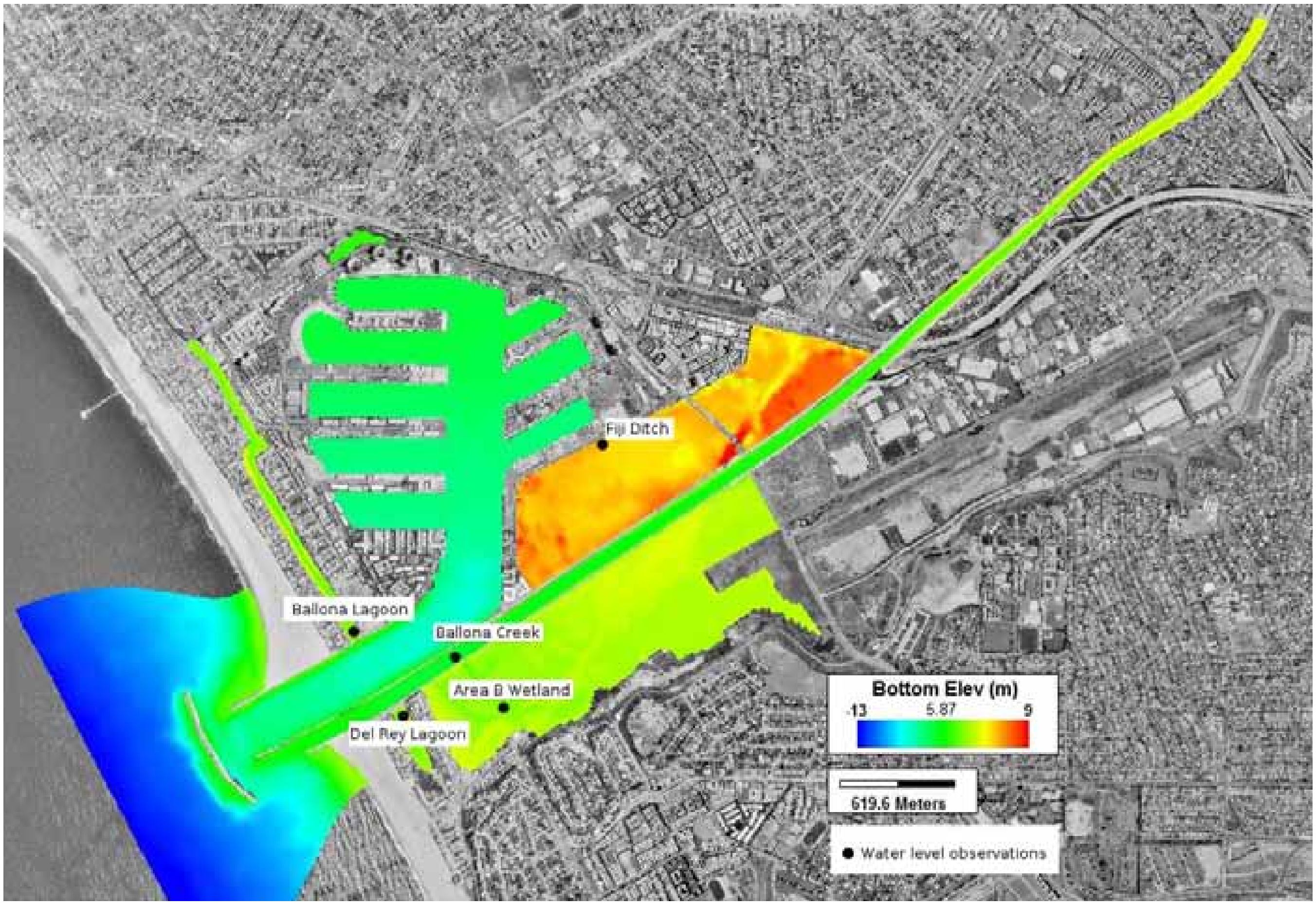

FIG. 4. EFDC model extent for Alternative 0. Figure courtesy of PWA (2008).

Hydrological Modeling

The primary models applied in this study are the Environmental Fluid Dynamics Code (EFDC) for simulating the hydrologic processes in the wetlands and the Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS) for simulating the primary hydrologic processes of the watershed (excluding the wetlands). The EFDC is a state-of-the-science hydrodynamic model that can be used to simulate aquatic systems in one, two, and three dimensions (Hamrick 1992; Tetra Tech. 2002). The model includes the primary physical processes important to the Ballona Wetland system, including unsteady tidal flow, boundary wetting and drying, and hydraulic control structures, and has been extensively applied and calibrated over the BWER (PWA, 2008). In this study, the model has been configured to predict two-dimensional depth-averaged flow. Overall, depending on the scenario (Alt0 [existing condition], Alt5, and RevAlt5), the model domain has approximately 43,000 grid cells (Fig. 4–5) and verification experiments using the Alt0 configuration accurately predicted water levels, typically within 5 cm of observations, over a two-week period (PWA 2008).

HEC-HMS is a modeling system used to represent the watershed rainfall-runoff process. This study implements a HEC-HMS beta configuration of the Ballona Creek Watershed developed and calibrated by the Los Angeles district of the Army Corps of Engineers (USACE 2012). The model domain decomposed the Ballona Creek watershed into 42 sub-basins and the major watershed characteristics incorporated as model elements include basin roughness (“n”) values, baseflow, rainfall data, soil loss rate, S-graph, channel routing, and model calibration. The model parameters are estimated through field investigation of the watershed according to the guidelines described in the USACE Ballona Creek Ecosystem Restoration Feasibility Study (USACE, 2012), and the models were calibrated using data from a rain gage located in the watershed and flow gage in the creek. Various flood scenarios based on the 100-year precipitation event were simulated and used as input for the upstream boundary of the EFDC model.

Tidal and Flood Simulation

To simulate the hydrologic conditions of the wetlands, the time-varying boundary conditions required by EFDC were set in the form of tidal heights for the ocean and discharge from the watershed generated by HEC-HMS. Two sets of simulations were conducted. The first, referred to as *tidal,* requires only time-varying tidal boundary conditions from the ocean. The second set, referred to as *flood,* requires time-varying boundary conditions from both the ocean and watershed. Each set of the above experiments was applied under various sea level rise (SLR) and/or extreme precipitation conditions to the two wetland restoration alternatives.

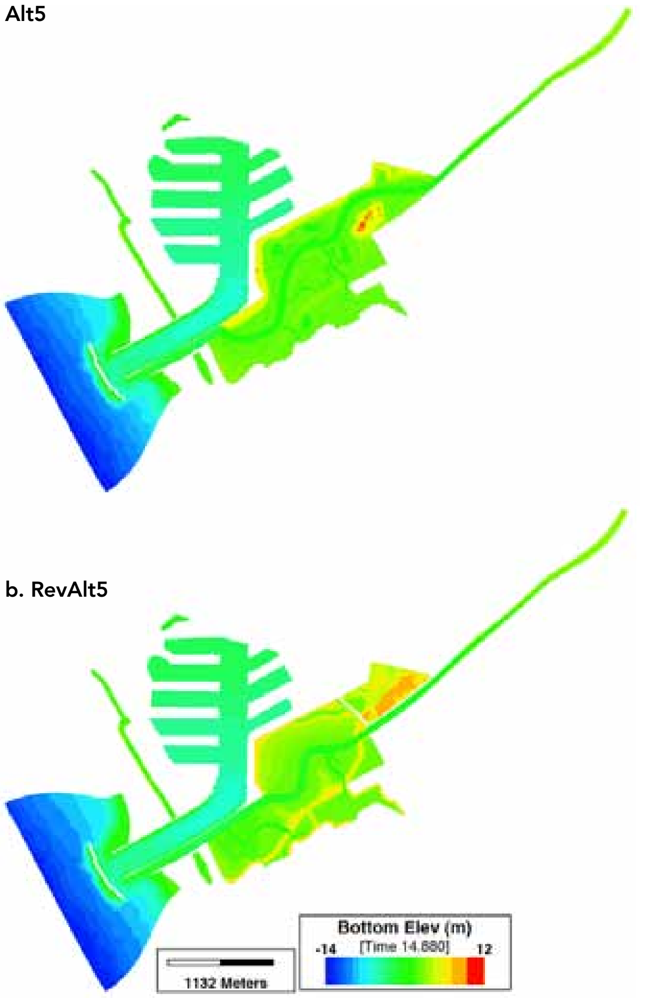

FIG. 5. Maps of EFDC bottom elevation for the restoration Alternative 5 (Alt5) (a) and revised restoration alternative 5 (RevAlt5) (b).

Scenario	Tidal Boundary Conditions	Sea Level Rise (cm)	Precipitation Event Boundary Conditions
Alternative 5	July 11–30 (No Flood): 6 simulations (3 for each alternative)	0	No Flood
Revised Alternative 5	July 6, Peak at Flood: 30 simulations (15 for each alternative)	100	100 yr - 25%
		140	100 yr - 10%
			100 yr
			100 yr + 10%
			100 yr + 25%

TABLE 1. List of scenarios and ocean and upstream boundary conditions. Note that each boundary condition is run under each scenario.

In the tidal simulation set, the role of tidal cycles alone on the wetland hydrology is investigated for the two restoration alternatives. Runoff generated from precipitation is assumed to be negligible. The tidal heights are specified for a representative spring-neap cycle from July 11 to July 30, 2006. Water surface elevations and inundation levels at current sea level conditions are compared to those at 100 and 140 cm of SLR. In total, there are six simulations: one for each of three SLR scenarios for each of the two restoration alternatives.

In the second simulation set, referred to as flood, both the role of tidal cycles and the role of extreme flooding on wetland inundation levels are considered. The output storm flow hydrographs simulated by HEC-HMS, based on the precipitation input, provide the Ballona Creek discharge into the BWER. Five scenarios based on the 100-year precipitation event are simulated using the HEC-HMS modeling system: The 100-year precipitation, which is considered the baseline event, and the 100 year with decreases and increases of 10% and 25%. The resulting hydrographs are applied as input to EFDC at Sawtelle, Sepulveda Channel, and Centinela Channel for each of the two restoration alternatives. In EFDC, the ocean boundary condition is forced by a typical 1.5-day tidal cycle with zero, 100, and 140 cm SLR. The peak of the hydrograph is timed such that it coincides with the higher high tide peak so that maximum wetland inundation occurs. In summary, a suite of 36 flood simulations were performed, as shown in Table 1.

Results

Impacts of Sea Level Rise—Tidal Simulations

This experiment investigated the impacts of SLR only on the two proposed restoration alternatives through tidal simulations. Input tidal levels varied from approximately -0.2 to 2.1 m, 0.8 to 3.1 m, and 1.2 to 3.5 m in the simulations with no SLR, SLR of 100 cm, and SLR of 140 cm, respectively. The EFDC model output suggests that with no SLR, the inundation areas with Alt5 ranged from 0.45 km^2 (19% of the wetland area) to 1.71 km^2 (74%), with a mean inundation area of 0.81 km^2 (35%; Fig. 6a,b, 7a,b, and Table 2). In contrast, the wet-dry active range with RevAlt5 was comparatively smaller, with inundation areas ranging from 0.32 km^2 (14%) to 0.65 km^2 (29%) and a mean area of 0.41 km2 (18%; Fig. 6c,d, 7c,d and Table 2). Note that these numbers were likely to be higher, since lower and higher tides, as well as storm surges occurring throughout the year, were not considered in the simulations.

In the event of SLR, the modeling output suggests that higher tides and subsequent higher water levels in the BWER will occur (Fig. 6 and 7). For Alt5, the wet-dry active range remained similar to the no SLR scenario (1.30 km^2 or 56%), while the mean inundation area substantially increased to 1.55 km2 (67%)—an increase of 0.74 km^2 (32%) with 100 cm of SLR and an additional increase to 1.76 km^2 (76%) with 140 cm of SLR. For RevAlt5, in contrast, with 100 cm of SLR, the wet-dry active range increased to 0.92 km^2 (41%), while the mean inundation area increased to 1.35 km^2 (59%). These numbers further increased with 140 cm of SLR to a wet-dry active range of 0.99 km^2 (43%) and mean inundation area of 1.63 km^2 (71%). The

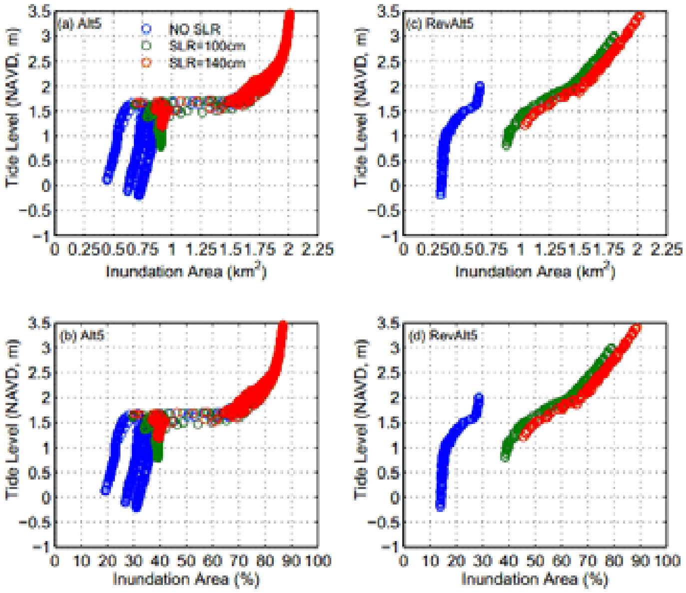

FIG. 6. Tidal simulations: Wet area versus tide level for no sea level rise (blue), 100 cm sea level rise (green), and 140 cm sea level rise (red) for both restoration alternatives; (a) Alt5 inundation area in km², (b) Alt5 inundation area in percent, (c) RevAlt5 inundation area in km², and (d) RevAlt5 inundation area in percent.

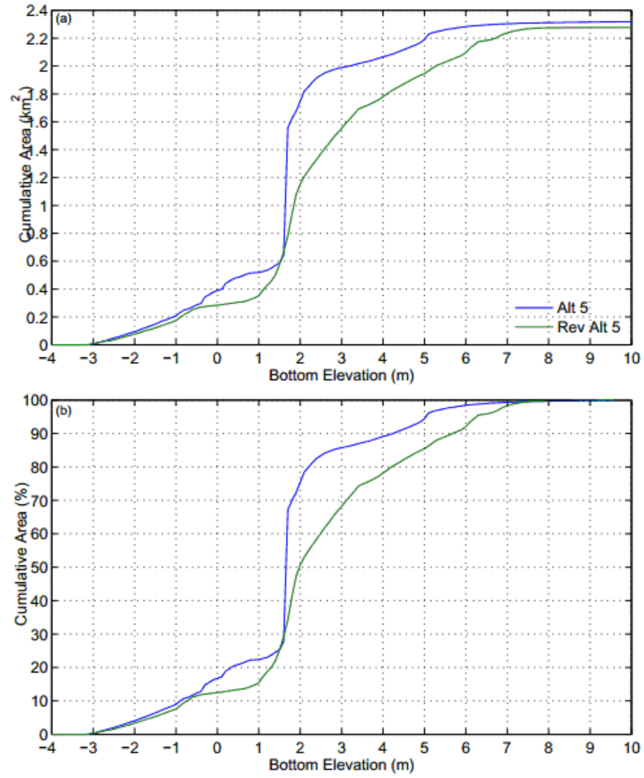

FIG. 8. Cumulative wetland area as a function of bottom elevation.

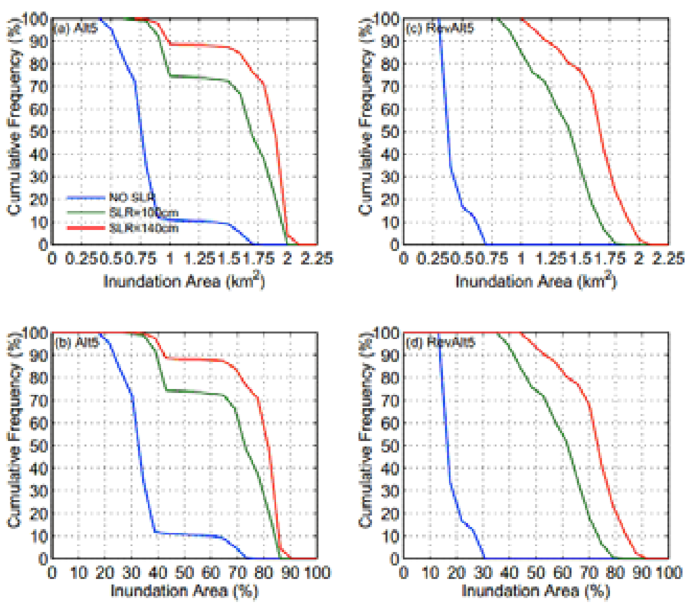

FIG. 7. Tidal simulations: Inundation area cumulative frequency for no SLR (blue), 1.0 m SLR (green), and 1.4 m SLR (red); (a) Alt5 inundation area in km², (b) Alt5 inundation area in percent, (c) RevAlt5 inundation area km², and (d) RevAlt5 inundation area in percent.

large shift in mean inundation levels with SLR is largely determined by the bottom elevation of the wetlands. In Alt5, 0.91 km² (29%) of the wetland area lay in the 1.6 to 1.7 m elevation zone (Fig. 8). Both the 100 and 140 cm SLR projections resulted in a shift in mean inundation levels to above the 1.6 to 1.7 m elevation range (comparing Fig. 6 and 8). On the other hand, the more gradual shift in RevAlt5 elevation zones (Fig. 8) tends to result in less change in inundation area and an increased resilience to SLR.

Impacts of Changes in Precipitation Event Magnitude—Flood Simulations

Flood hydrographs modeled by HEC-HMS for both restoration alternatives show that the impacts of 10% and 25% decreases and increases to the 100-year precipitation event in general resulted in a disproportionally smaller or larger volume of flood discharge entering the wetlands. For example, the 10% and 25% reductions in the 100-year precipitation event resulted in 14% and 36% reductions in watershed flood discharge entering the wetlands, reducing the flood return periods to approximately 50 and 10 years, respectively. Similarly, 10% and 25% increases in the 100-year precipitation resulted in 14% and 35% increases in watershed discharge, which are comparable to approximately the 200-year event and the greater than 500-year event, respectively. These results suggest that nonlinearities inherent in the system such as those related to infiltration processes in the watershed amplify the response of storm flow to changes in precipitation. In addition, they imply that

	Alternative 5 – Tidal						Revised Alternative 5 – Tidal					
	No SLR		SLR = 100 cm		SLR = 140 cm		No SLR		SLR = 100 cm		SLR = 140 cm	
	km²	%	km²	%	km²	%	km²	%	km²	%	km²	%
Mean	0.81	35%	1.55	67%	1.76	76%	0.41	18%	1.35	59%	1.63	71%
Minimum	0.45	19%	0.68	29%	0.70	30%	0.32	14%	0.88	39%	1.04	45%
Maximum	1.71	74%	1.99	86%	2.01	87%	0.65	29%	1.80	79%	2.02	89%
Range	1.26	55%	1.30	56%	1.31	57%	0.34	15%	0.92	41%	0.99	43%

TABLE 2. Mean, minimum, and maximum inundation area (km2) according to the alternative and SLR scenario.

	Maximum Inundated Area Alternative 5 – Flood Simulations									
	T=100yr-25%		T=100yr-10%		T=100yr		T=100yr+10%		T=100yr+25%	
	km²	%	km²	%	km²	%	km²	%	km²	%
No SLR	1.16	50%	1.44	62%	1.64	71%	1.83	79%	1.92	83%
SLR=100 cm	1.90	82%	1.93	83%	1.95	84%	1.97	85%	1.99	86%
SLR=140 cm	1.97	85%	1.98	85%	1.99	86%	2.00	86%	2.03	87%
	Maximum Inundated Area Revised Alternative 5 – Flood Simulations									
	T=100yr-25%		T=100yr-10%		T=100yr		T=100yr+10%		T=100yr+25%	
	km²	%	km²	%	km²	%	km²	%	km²	%
No SLR	1.74	76%	1.86	81%	1.93	85%	2.00	88%	2.04	90%
SLR=100 cm	1.98	87%	2.03	89%	2.05	90%	2.06	90%	2.07	91%
SLR=140 cm	2.04	90%	2.06	90%	2.06	91%	2.07	91%	2.08	91%

TABLE 3. Flood simulation—Maximum inundation area in km2 and % for each of the flood with and without SLR simulations. Upper table is for Alt5 and lower is for RevAlt5.

small changes in future precipitation may result in large changes in watershed response.

For Alt5 with the baseline flood event (T=100 years), the maximum BWER inundation area modeled by EFDC was 1.64 km^2 (71%; Fig. 9 and Table 3). Locations near developed areas were inundated during this event, such as at Jefferson Blvd and Lincoln Blvd (Fig. 9a). For such a large storm, however, some amount of flooding is generally expected. The maximum wetland inundation area varied from 1.16 km^2 (50%) to 1.44 km^2 (62%) under the 25% and 10% reduction scenarios, respectively. Under the 10% and 25% increase scenarios, maximum inundations levels were 1.83 km2 (79%) and 1.92 km^2 (83%), respectively (Fig. 9 and Table 3). In these scenarios, much of the area near the bluffs along the southern boundary of the BWER were also flooded (Fig. 9d,e).

For RevAlt5, maximum inundation area were 1.93 km^2 (85%) for the baseline flood simulation (T=100yr; Fig. 10 and Table 3). Although the far eastern portion of the BWER and the area south of the creek levees appeared to be inundated as a result of the flood, they were actually inundated due to the initial water elevations being set to the tidal levels (Fig. 10). On the other hand, changes in the 100-year precipitation and associated flood event for RevAlt5 resulted in a range of maximum inundation areas considerably smaller than the Alt5 simulations (1.74 to 2.04 km2 for T=100yr-25% or 76 to 90% for T=100yr+25%), similar to the tidal simulations (Fig. 10 and Table 3), suggesting a greater resilience to flooding.

Combined Impacts of Sea Level Rise and Changes in Precipitation Event Magnitude

In these model simulations the combined impacts of sea level rise and changes in the precipitation event magnitude for both restoration alternatives were analyzed. Specifically, sea level rise conditions were applied to the tidal cycle with the various changes in flood frequency, as is done in the tidal simulations. First, the simulation was analyzed for both restoration alternatives when SLR was considered with no change in the 100-year precipitation event magnitude. The result shows that significant wetland inundation occurred at approximately day 6.2—well before any significant flood entered the wetlands from the watershed (Fig. 11). This inundation

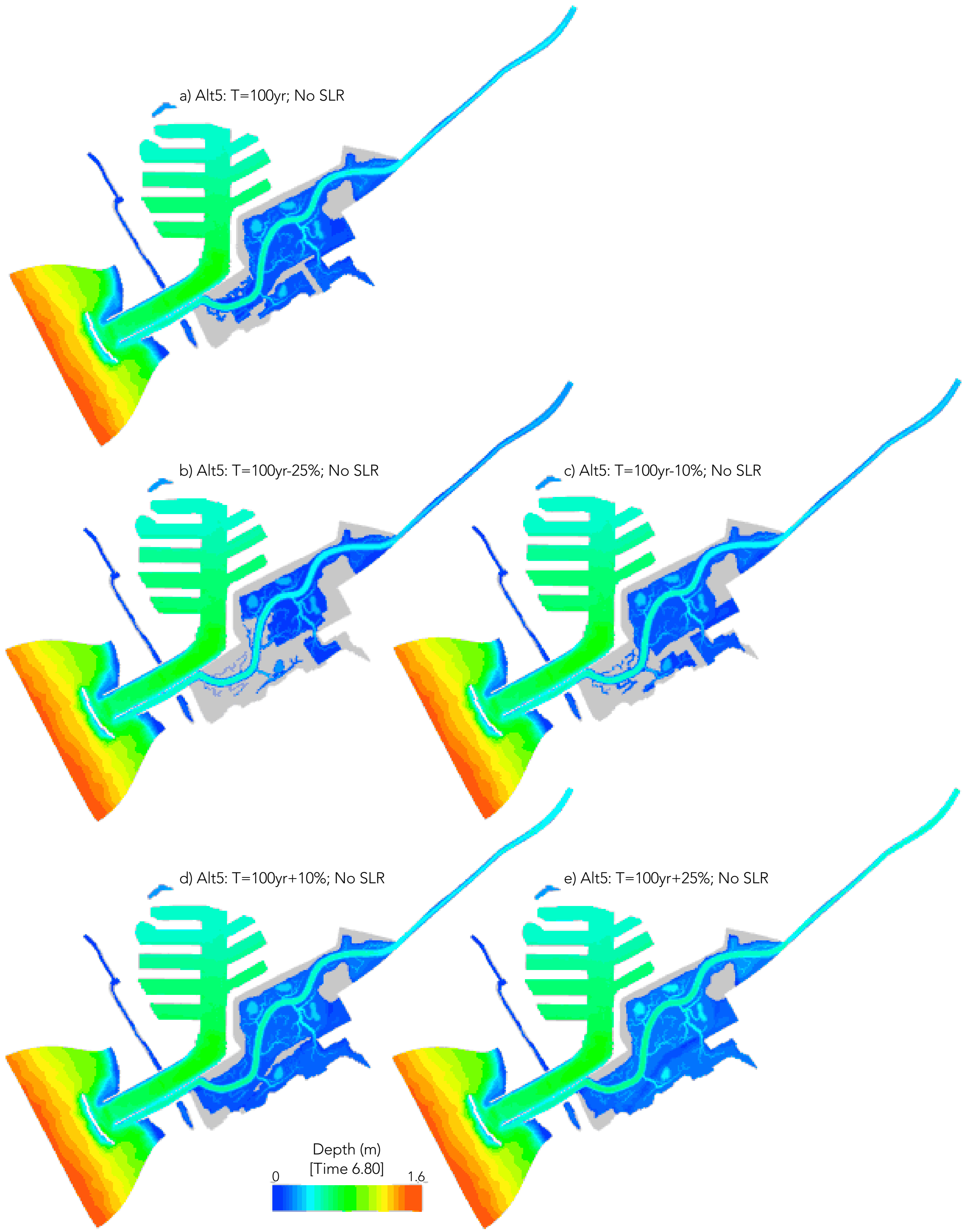

FIG. 9. Flood Simulations: Alt5 – Water depths (m) at maximum inundation (time = 6.80) for the 100-year precipitation event; a) T=100 yr, b) T=100 yr - 25%, c) T=100 yr - 10%, d) T=100 yr +10%, and e) T=100 yr +25%.

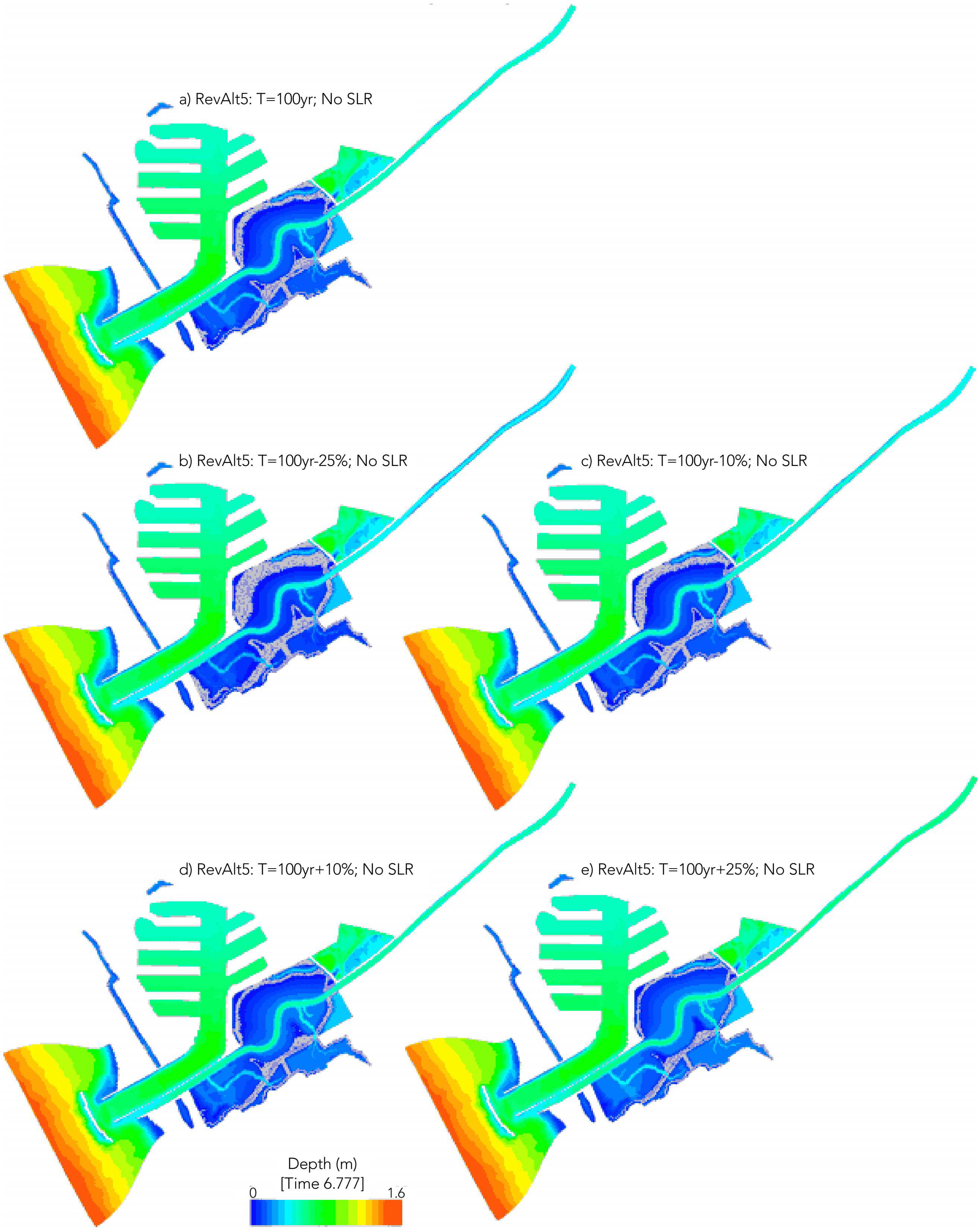

FIG. 10. Flood simulations: RevAlt5 – Water depths (m) at maximum inundation (time = 6.777) for the 100-year precipitation event; a) T=100 yr, b) T=100 yr - 25%, c) T=100 yr - 10%, d) T=100 yr +10%, and e) T=100 yr +25%.

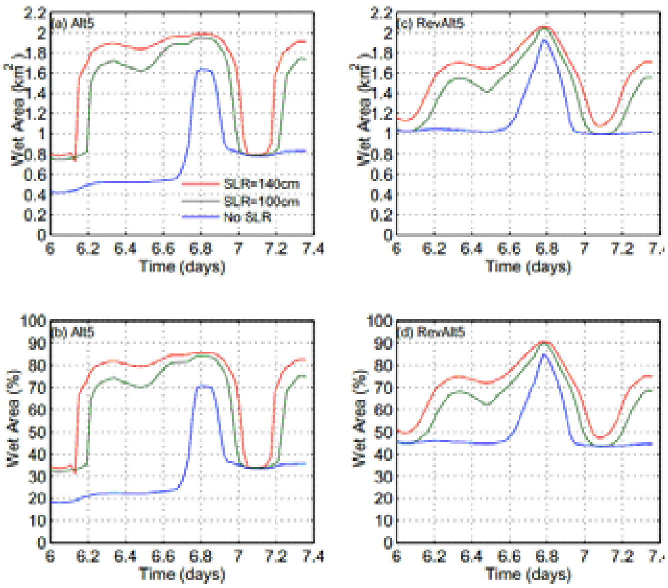

FIG. 11. Flood simulations with SLR: Wet area versus time resulting from the 100-yr precipitation event for the three sea level rise scenarios for Restoration Alternative 5 and Revised Alternative 5. Notice that the tidal cycle in these simulations is timed such that its peak occurs at the flood hydrograph peak at approximately day 6.8. In addition, the flood discharge completely subsides at approximately day 7.1.

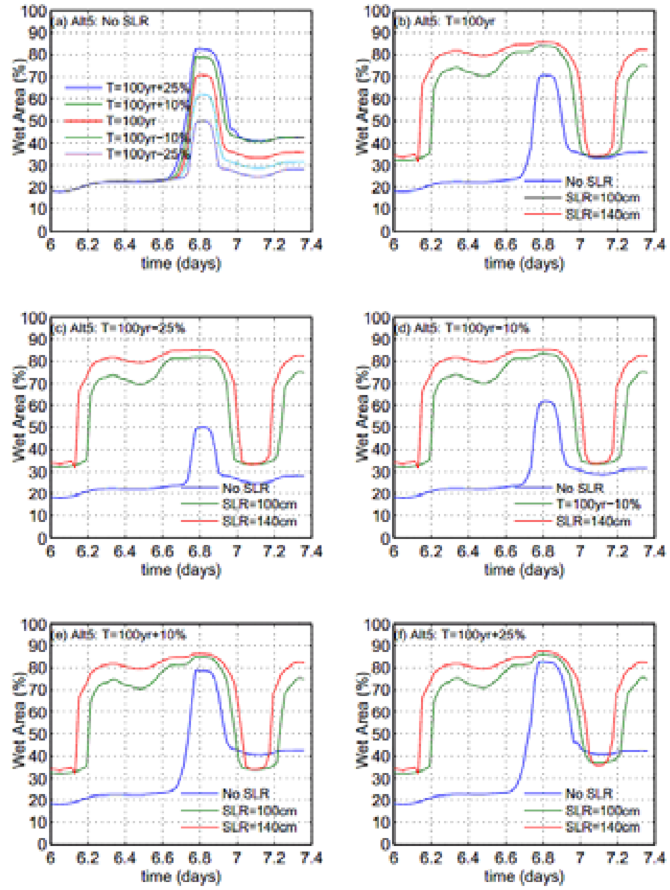

FIG. 12. Flood simulations with SLR: Wet area versus time for the five flood scenarios for Restoration Alternative 5.

persisted at nearly the same level until the flood and higher high tide occurred. Furthermore, another inundation peak occurred at approximately day 7.3 after the watershed flood discharge had completely subsided (Fig. 11). This peak coincided with the lower high tide of day 7 on the following day. In short, SLR dominated the response of wetland inundation to flooding, particularly with the Alt5 scenario. RevAlt5 displayed a similar but weaker response despite starting at a higher water level.

When considering the combination of SLR with changes in extreme precipitation event magnitude for Alt5, the wetland inundation levels remained similar regardless of the change in precipitation event magnitude (Fig. 12). Even with the 25% reduction scenario resulting 36% decrease in discharge, the wetland inundations levels remained at 80% until the higher high tide droped at day 7.0. This result is similar for RevAlt5 (Fig. 13).

Impacts of Sea Level Rise on Habitat Conditions

Types of estuarine habitats within the existing BWER include sub-tidal and intertidal channels, mudflats, salt flats, low marsh, marsh plain (or mid marsh), high marsh, high marsh transition zone, and brackish marsh. Although multiple factors contribute to the types and acreages of habitats within the BWER, the period, depth, and frequency of tidal inundation is considered a major factor (Warren and Nierling 1993; Donnelly and Bertness 2001; Greer and Stow 2003; Watson and Byrne 2009), and subjects most to the impacts of climate changes. For these reasons, we used the modeled changes to the hydrology and hydraulics of the wetlands discussed above to predict the changes in habitat distribution and acreage under the two restoration alternatives. Because, as discussed above, increased precipitation has very little effect on the hydrology of the system when sea level rise is included in the scenario, we reasonably assumed that the migration of wetland habitats is largely driven by SLR, and considered the implications of increased sea level only in this analysis. In addition, change in elevation instead of inundation frequency was used to predict the effects of SLR on habitat distribution and acreage in this analysis. Previous EFDC modeling on habitat areas have shown that elevation can provide a surrogate for inundation frequency as the results based on either are in general comparable.

All major types of estuarine habitats within the existing BWER listed above were investigated. Both Alternative 5 and the Revised

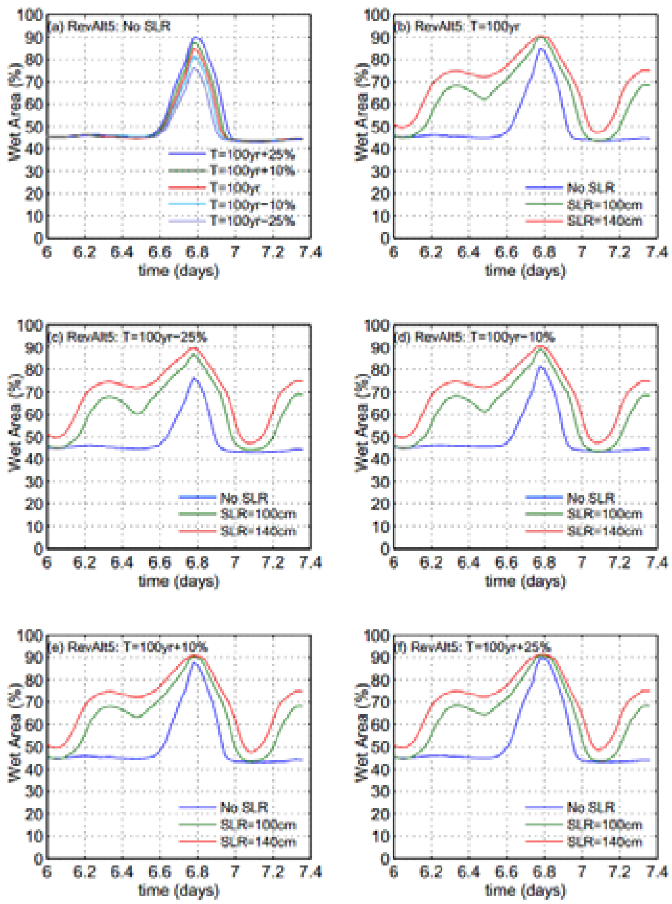

FIG. 13. Flood simulations with SLR: Wet area versus time for the five flood scenarios for Revised Restoration Alternative 5.

Alternative (Fig. 3) are expected to yield the same habitat types as currently exist in the BWER, but with conditions more representative of a natural wetland with reduced impacts from urban development. Figure 14 displays the effects of SLR on the habitat distributions under Alt5. With current SL conditions, restoration Alternative 5 supported a large mid salt marsh plain (1.1 km^2) typical of Southern California coastal wetlands. However, with SLR, this middle marsh habitat transitioned to mudflat habitat (1.31 km^2 with 1.0 m SLR, and 1.38 km^2 with 1.4 m SLR) assuming static conditions of other physical influences such as scour or sedimentation. The transition from a vegetated middle marsh wetland system to a mudflat-dominated system will cause dramatic shift in the species supported. For example, there may be a significant loss of Belding's savannah sparrow habitat with SLR due to the bird's dependency on marsh habitat for breeding.

Habitat distributions were investigated for the revised restoration alternative using similar methods to Alt5. RevAlt5 modified the previous Alt5 and included a continuous slope throughout the marsh habitat that extends into the transitional and upland habitats. This minor change may provide significant benefits, including extending the persistence of intertidal marsh habitats based on the ability of those habitat types to transgress up the margins of the marsh. The modeled prediction on the habitat distributions shows that RevAlt5 may provide such benefit. Under RevAlt5 and with current SL conditions, the revised restoration alternative supported a range of vegetated marsh habitat (0.86 km^2). With SLR, this alternative also shifted toward a mudflat dominated system (0.86 km^2 with 1.0 m SLR, and 0.91 km^2 with 1.4 m SLR). However, the revised alternative continued to support a significant area of diverse marsh habitats (0.41 km^2 with 1.0 m SLR, and 0.31 km^2 with 1.4 m SLR) (Fig. 15).

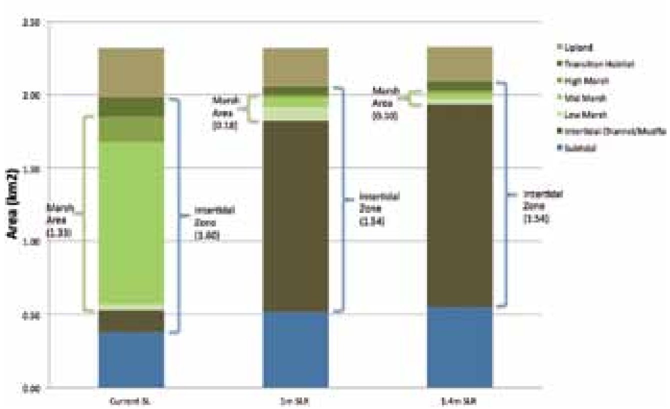

FIG. 14. Restoration Alternative 5 habitat area with current SL and 1.0 m and 1.4 m SLR.

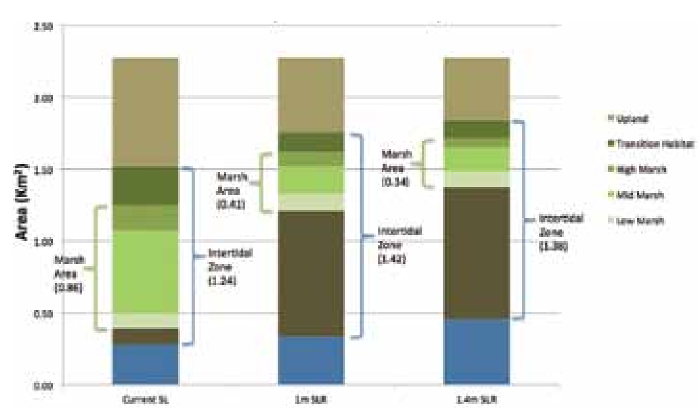

FIG. 15. Revised Restoration Alternative 5 habitat area with current SL and 1.0 m and 1.4 m SLR.

Discussion

This study used hydrological and hydraulic modeling to investigate the impacts of SLR and changes of precipitation event magnitude on two restoration alternatives being developed for the BWER. The results demonstrate that in the event of SLR (with SLR estimates of 1.0 m and 1.4 m in the year 2100), habitats restored according to either alternative will experience various levels of impacts. On the other hand, when SLR is included in the scenario, changes in precipitation event magnitudes have little effect on the hydrology of the system for both alternatives.

The results of the study also demonstrate that a restoration alternative that can accommodate the transgression of habitats upslope may provide more sustainability in the long term. The steep, then flat, then steep system of Alt5 is well designed to accommodate current sea level conditions. However, it is not resilient to SLR impacts because the wetlands remain largely inundated even at lower tides under SLR scenarios. In contrast, RevAlt5 is more resilient to SLR because more of the wetlands experiences both dry and wet conditions under the SLR scenarios. In future restoration planning for coastal habitats, it may be useful to model the impacts of sea level rise on designs that provide flat marsh areas on a stepped, rather than continuously sloped, gradient. Incremental steps of marsh at various elevations may maintain larger areas of a given marsh habitat as sea levels rise.

The results of this study validate one of the widely-held assumptions that tidal wetlands in Southern California, including the BWER, are inherently highly vulnerable to SLR because they typically exist within a very narrow elevation range set primarily by the tidal frame (high and low tides), which is approximately 2 m in the region. A small change in the tidal frame due to SLR would result in migration of the vertically distributed tidal habitats. Meanwhile, it should be noted that the response of tidal wetlands to SLR also depends on many other factors that were not investigated under this study. One of the key factors is the availability of space for the transgression of wetland habitats to higher elevations. Another is sediment supply to the wetland and the associated rate of wetland accretion. If sediment is readily available, vertical accretion may keep pace with SLR and the spatial distribution of tidal habitats may not change significantly. If sediment supply is low, as in the urbanized Ballona Creek, accretion rates may be slower than SLR and habitats would transgress landward, if there is space for them to do so. The restriction on tidal flow caused by the existing tide gates in the creek levee should also be further investigated because these gates prevent full high tide from entering the wetlands and therefore further limit the ability of the wetlands to respond to the SLR. Finally, further studies may need to consider the effect of ponding water on habitat distributions because ponding may become more frequent and persistent, and ponds may become larger and deeper as sea levels rise.

This study also investigated the impacts of climate change on the habitat structure and function in coastal wetlands, mainly as a result of increased inundation frequency due to SLR. This is important as previous research in other regions such as the San Francisco Estuary wetlands and the New England salt marshes suggests that wide-scale vegetation change is already occurring due to sea level rise (Donnelly and Bertness 2001; Watson and Byrne 2009). The results indicate that with SLR, such changes could also occur in BWER, to various degrees under different restoration alternatives. However, these results are still preliminary and limited to general habitat type only. In the future, an investigation of the species supported by these habitats and the potential change in species composition and diversity could be developed from the SLR projections.

Modeling System Constraints and Considerations for Further Application

In this study, a suite of simulations using both a watershed rainfall-runoff model (HEC-HMS) and a wetlands model (EFDC) were performed to investigate the potential impacts of climate change on two BWER restoration alternatives. While considerable and reliable information is provided from this suite of simulations, the results are preliminary, and several improvements can be made.

First, although extensive work has gone into calibrating the model for the Ballona Watershed and simulated hydrographs resulting from the 100-year precipitation event (and other return periods) match observations remarkably well, the configuration is still in a testing phase, and improved model parameters in a new model configuration expected to be released by ACOE in the near future will hopefully better represent the rainfall-runoff processes of the watershed. For the tidal simulations in this study, the EFDC configuration and calibration did not include processes for infiltration, evapotranspiration, and direct precipitation falling onto the wetlands. These, particularly direct precipitation, may be an important component of a wetland water budget and should be considered in similar studies in the future. An ideal next step would be a yearlong set of simulations that include these parameters and is associated with a large El Nino event that generated considerable precipitation and stormflow into the wetlands. Furthermore, additional experiments with a larger extended domain and/or flux boundaries should be performed in the future to address the potential inundation of areas in the surrounding community and to test the robustness of a revised RevAlt5. Finally, additional experiments should be designed to investigate the scenario of a large storm event coinciding with storm surge, which is rather typical and which impacts may be underestimated in this study.

In summary, this study explored a new approach to integrate climatic and hydrological models, and demonstrated its applicability in assessing the impacts of climate change on coastal wetland habitats. The applicability of this new modeling tool may be more important than the results of analysis on the two restoration alternatives. Since at the time of this paper's publication the Ballona Wetland restoration planning process is still ongoing, and restoration alternatives are still evolving, new model runs for the updated restoration alternatives may provide more representative and reliable assessment of the climate change impacts.

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References

Bell, J. L., L. C. Sloan, and M. A. Snyder. 2004. "Regional Changes in Extreme Climatic Events: A Future Climate Scenario. *Journal of Climate*. 17(1):81–87.

BWRP (Ballona Wetlands Restoration Project). 2012. "Ballona Wetlands Restoration Project Fact Sheet." Ballona Wetlands Restoration Project Website. http://www.santamonicabay.org/BWRP/BWRP_Documents.

CO-CAT (Coastal and Ocean Working Group of the California Climate Action Team). 2010. "State of California Sea-Level Rise Interim Guidance Document." http://www.opc.ca.gov/webmaster/ftp/pdf/agenda_items/20100911/14.%20SLR/1011_COPC_SLR_Interim_Guidance.pdf.

Diffenbaugh, N. S., J. S. Pal, R. J. Trapp, and F. Giorgi. 2005. "Fine-Scale Processes Regulate the Response of Extreme Events to Global Climate Change." *Proceedings of the National Academy of Sciences of the United States of America* 102(44):15774–78.

Donnelly, J. P., and M. D. Bertness. 2001. "Rapid Shoreward Encroachment of Salt Marsh Cordgrass in Response to Accelerated Sea-Level Rise." *Proceedings of the National Academy of Sciences of the United States of America* 98(25):14218–23.

Greer, K., and D. Stow. 2003. "Vegetation Type Conversion in Los Peñasquitos Lagoon, California: An Examination of the Role of Watershed Urbanization." *Environmental Management,* 31: 489-503.

Hamrick, J. M. 1992. *A Three-Dimensional Environmental Fluid Dynamics Computer Code: Theoretical and Computational Aspects*. Special report 317. College of William and Mary, Virginia Institute of Marine Science.

Higgins, R. W., V. B. S. Silva, W. Shi, and J. Larson. 2007. "Relationships Between Climate Variability and Fluctuations in Daily Precipitation over the United States." *Journal of Climate* 20(14):3561–3579. doi:10.1175/JCLI4196.1.

IPCC (Intergovernmental Panel on Climate Change). 2007. *Fourth Climate Change Assessment Report*. Oslo, Norway.

Karl, T. R., and R. W. Knight. 1998. "Secular Trends of Precipitation Amount, Frequency, and Intensity in the United States." *Bulletin of the American*. Meteorological Society 79:231–41.

———, J. M. Melillo, and T. C. Peterson. 2009. *Global Climate Change Impacts in the United States*. Cambridge: Cambridge University Press. http://downloads.globalchange.gov/usimpacts/pdfs/climate-impacts-report.pdf.

Kim, J. 2005. "A Projection of the Effects of the Climate Change Induced by Increased CO_2 on Extreme Hydrologic Events in the Western U.S. *Climatic Change* 68:153–68.

Madsen, T., and E. Figdor. 2007. *When It Rains It Pours: Global Warming and Rising Frequency of Extreme Precipitation in the United States*. *Environment America*. http://www.environmentamerica.org/sites/environment/files/reports/When-It-Rains-It-Pours----US---WEB.pdf.

Mass, C., A. Skalenakis, and M. Warner. 2010. "Extreme Precipitation over the West Coast of North America: Is There a Trend?" *Journal of Hydrometeorology* 12(2):310–318 doi:10.1175/2010JHM1341.1.

Pryor, S. C., J. A. Howe, and K. E. Kunkel. 2009. "How Spatially Coherent and Statistically Robust are Temporal Changes in Extreme Precipitation in the Contiguous USA?" *International Journal of Climatology* 29:31–45.

PWA. 2006. *Ballona Creek Wetlands Existing Conditions Report*. Prepared for the California State Coastal Conservancy. http://www.santamonicabay.org/BWRP/bwrpdocuments.html.

———. 2008. *Ballona Creek Wetlands Restoration Feasibility Report*. Prepared for the California State Coastal Conservancy. http://www.santamonicabay.org/BWRP/bwrpdocuments.html.

Silvestri, S., A. Defina, and M. Marani. 2005. "Tidal Regime, Salinity, and Salt Marsh Plant Zonation." *Estuarine, Coastal and Shelf Science* 62:119–30.

Tetra Tech. 2002. *User's Manual for Environmental Fluid Dynamics Code: Hydro Version (EFDC-Hydro)*. Prepared for US Environmental Protection Agency.

USACE. May 2012. *Ballona Creek Ecosystem Restoration Feasibility Study Baseline Conditions Report*. US Army Corps of Engineers South Pacific Division Los Angeles District.

Vermeer, M., and S. Rahmstorf. 2009. "Global Sea Level Linked to Global Temperature." *PNAS*. doi/10.1073/pnas.0907765106.

Warren, R. S., and W. A. Niering. 1993. "Vegetation Change on a Northeast Tidal Marsh: Interaction of Sea-Level Rise and Marsh Accretion. *Ecology* 74(1):96–103.

Watson, E. B., and R. Byrne. 2009. "Abundance and Diversity of Tidal Marsh Plants Along the Salinity Gradient of the San Francisco Estuary: Implications for Global Change Ecology." *Plant Ecology* 205:113–28.

Zedler, J. B., and G. W. Cox. 1985. "Characterizing Wetland Boundaries: A Pacific Coast Example." *Wetlands* 4:43–55.